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14. ABSTRACT
The research activities included observational, as well as theoretical aspects of the coronal and interplanetary propagation of coronal mass ejections (CMEs)..

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Reference:
FA8655-06-1-3036

"Space Weather: Forecasting the Arrival of Coronal Mass Ejections"
(official starting date: May 15, 2006)

FINAL REPORT ON RESEARCH ACTIVITIES AND RESULTS

A) BRIEF DESCRIPTION OF THE RESEARCH

The research activities included observational, as well as theoretical aspects of the coronal and interplanetary propagation of coronal mass ejections (CMEs). The research was carried out primarily by four researchers: Bojan Vršnak (PI; Hvar Observatory), Manuela Temmer (Hvar Observatory), Darije Maričić (Astronomical Observatory Zagreb), and Astrid Veronig (Karl-Franzens Universitaet Graz, Austria). In addition, three PhD students employed at Hvar Observatory (Davor Sudar, Domagoj Ruždjak, and Tomislav Žic) were engaged in certain aspects of the research and provided a significant support in the project activities.

Until now, the results are published in five scientific papers, two are in press, one is submitted, and four are in preparation.

Summary of results:

1. An empirical relationship between the area/position of coronal holes (CHs) and the characteristics of the associated high-speed streams (HSSs) in the solar wind is established. A procedure is developed, providing forecasting of the HSS velocity and density, which are important parameters for estimating the Sun-Earth transit times of interplanetary coronal mass ejections (ICMEs).
(reported in B. Vršnak, M. Temmer, & A.M. Veronig: *Coronal holes and solar wind high-speed streams: I. Forecasting the solar wind parameters*, **Solar Phys. 240,** 315-330 (2007) available online at http://dx.doi.org/10.1007/s11207-007-0285-8)

2. The analysis of the area/position of coronal holes revealed also a distinct relationship between the CH characteristics and the severity of the HSS-associated geomagnetic storm. The relationship provides forecasting of *Dst* changes several days in advance.
(reported in B. Vršnak, M. Temmer, & A.M. Veronig: C*oronal holes and solar wind high-speed streams: II. Forecasting the geomagnetic effects*, **Solar Phys. 240,** 331-346 (2007); available online at http://dx.doi.org/10.1007/s11207-007-0311-x)

3. It is found that in the declining phase of the solar cycle CHs were distributed very regularly over the solar surface, on average being separated by 120 deg. Such a triangular pattern results in nine days periodicity in the solar wind characteristics and the geomagnetic activity.
(reported in M. Temmer, B. Vršnak, and A.M. Veronig: *Periodic appearance of coronal holes and the related variation of solar wind parameters*, **Solar Phys.** in press (2007); available online at http://dx.doi.org/10.1007/s11207-007-0311-x)

4. Characteristics of the CME acceleration were studied employing a sample of 22 CMEs, in order to get a better insight into the processes and forces that govern the ICME take-off. The most important result is that initially compact CMEs are accelerated more impulsively than CMEs of extended source regions. The results are important for advancing the kinematical modeling of the interplanetary propagation of ICMEs.
(reported in B. Vršnak, D. Maričić, A.L. Stanger, A.M. Veronig, M. Temmer, & D. Roša: *Acceleration phase of coronal mass ejections: I. Temporal and spatial scales*, **Solar Phys. 241,** 85-98 (2007);
available online at http://dx.doi.org/10.1007/s11207-006-0290-3)

5. Synchronization of the acceleration of CMEs and the energy release in the associated flares was investigated in detail, employing the same data set. It is found that the feedback relationship exists in about one half of the events. However, in about one quarter of events these two phenomena are not synchronized. The results are important for comprehension of the role of magnetic reconnection during the ICME take-off.
(reported in D. Maričić, B. Vršnak, A.L. Stanger, A.M. Veronig, M. Temmer, & D. Roša: *Acceleration phase of coronal mass ejections: II. Synchronization of the energy release in the associated flare*, **Solar Phys. 241,** 99-112 (2007);
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6. Combining theoretical arguments and observations we inferred that the most powerful energy release in the CME-associated flare occurs at the location where the current sheet, which forms beneath the erupting flux-rope, has the largest vertical extent. This also implies that reconnection provides most of the "fresh" poloidal field to the summit elements of the CME, providing a prolonged acceleration of frontal parts of the CME.
(reported in M. Temmer, B. Vršnak, A.M. Veronig, and M. Miklenic: *Spatial restriction to HXR footpoint locations by reconnection site geometries* (**Cent. Europ. Astrophys. Bull. 31**, 49-56, (2007))

7. Since the true velocity of CMEs is essential for modeling their interplanetary propagation, we analyzed to what degree the projection effects influence measurements of the CME velocities. It was found that the projection effects are much smaller than expected from simple geometrical models like, e.g., the CME cone model. An empirical expression is established, relating the velocity correction and the location of the CME source region.
(reported in B. Vršnak, D. Sudar, D. Ruždjak, & T. Žic: *Projection effects in coronal mass ejections*, **Astronomy & Astrophysics**, in press, 2007)

8. We found that the Sun-Earth transit times (*TT*) of ICMEs depend significantly on the ambient solar wind speed *w*. Empirical expressions relating *TT* and the ICME take-off speed v_{CME} are derived, separately for different classes of the ambient solar wind speeds. In combination with results described in items 1 and 6, these relations provide an improved forecasting of ICME arrivals, where in more than 80% of cases the ICME arrival could be

predicted with an accuracy better than 10 hours. Furthermore, combining with theoretical arguments, it was demonstrated that the remaining data scatter is probably due to different masses/densities of ICMEs (to be studied further).
(reported in B. Vršnak & T. Žic: *Transit times of interplanetary coronal mass ejections and the solar wind speed*, **Astronomy & Astrophysics**, submitted March 2007)

9. A distinct correlation was found between ICME transit times and the location of the CME source region: ICMEs whose source region is located less than 30 deg from the solar disc center, on average arrive 5 hours earlier than those whose source is closer to the limb. (not published yet; to be studied further).

10. From the *in situ* measurements it was found that the thickness of the sheath layer between the shock and the ICME, on average amounts to 1/3 of the ICME thickness. The average sheath "thickness" is 6.5 hours. The thickness is smaller in faster ICMEs. The result is important for testing the kinematical modeling of the ICME propagation (not published yet; to be studied further).

11. We investigated the conditions for the MHD shock formation by impulsively expanding 3-dimensional pistons. In particular, the cylindrical and spherical pistons were considered in the high-beta and low-beta plasma. The dependence of the time/distance of the shock formation on the acceleration phase duration, maximum acceleration, maximum expansion speed, maximum Mach number, initial source dimension, and ambient Alfven velocity was analyzed, and it was found that the impulsiveness of the acceleration is the most important parameter (not published yet; to be studied further).

12. The model developed (item 11) was applied to one very well observed CME to reproduce the Moreton wave signature of the related coronal shock. It was shown that the required acceleration is much larger than that measured in the upward motion of the CME, indicating that either the lateral expansion of CME was initially much more impulsive than the vertical one, or that the shock was caused by the associated flare.

Presentations at Conferences:

1. WORKSHOP ON SOLAR FLARES AND INITIALISATION OF CMEs
   September 13-15, 2006, Tatranska Lomnica, Slovakia (**three presentations**)
   (http://www.astro.sk/~choc/open/06_wrkshp/06_wrkshp.html)
2. VIIIth Hvar Astrophysical Colloquium: DYNAMICAL PROCESSES IN THE SOLAR ATMOSPHERE
   September, 24-29 2006, Hvar, Croatia: (**two presentations**)
   (http://www.geof.hr/oh/)

B) US visitors
17-22. Sept. 2006: E. W. Cliver (AFRL, Hanscom)
23-30. Sept. 2006 G.W.P. York (EOARD)
23-30. Sept. 2006 N. Gopalswamy (NASA, GSFC)
24-28. Sept. 2006 N. Nitta (LMATC, Palo Alto)

C) PUBLICATION OF THE RESULTS

1. B. Vršnak, M. Temmer, & A.M. Veronig: *Coronal holes and solar wind high-speed streams: I. Forecasting the solar wind parameters*
Solar Phys. 240, 315-330 (2007);
available online at http://dx.doi.org/10.1007/s11207-007-0285-8

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available online at http://dx.doi.org/10.1007/s11207-007-0311-x

3. B. Vršnak, D. Maričić, A.L. Stanger, A.M. Veronig, M. Temmer, & D. Roša:
Acceleration phase of coronal mass ejections: I. Temporal and spatial scales
Solar Phys. 241, 85-98 (2007);
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4. D. Maričić, B. Vršnak, A.L. Stanger, A.M. Veronig, M. Temmer, & D. Roša:
Acceleration phase of coronal mass ejections: II. Synchronization of the energy release in the associated flare
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Cent. Europ. Astrophys. Bull. 31, 49-56, (2007)

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7. B. Vršnak, D. Sudar, D. Ruždjak, & T. Žic: *Projection effects in coronal mass ejections*
Astron. & Astrophys. in press, 2007

8. B. Vršnak & T. Žic: *Transit times of interplanetary coronal mass ejections and the solar wind speed*
Astron. & Astrophys. submitted March 2007

FINAL REPORT ON THE EOARD/AFRL PROJECT FA8655-06-1-3036

"Space Weather: Forecasting the Arrival of Coronal Mass Ejections"

The research activities included observational, as well as theoretical aspects of the coronal and interplanetary propagation of coronal mass ejections (CMEs). The research was carried out primarily by four researchers:

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Manuela Temmer (Hvar Observatory),

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In addition, three PhD students employed at the Hvar Observatory (Davor Sudar, Domagoj Ruždjak, and Tomislav Žic) were engaged in certain aspects of the research and provided a significant support in the project activities.

Until now, the results are published in five scientific papers, two are in press, one is submitted, and four are in preparation.

Results are published in:

B. Vršnak, M. Temmer, & A.M. Veronig: *Coronal holes and solar wind high-speed streams: I. Forecasting the solar wind parameters*
Solar Phys. 240, 315-330 (2007); available online at http://dx.doi.org/10.1007/s11207-007-0285-8

B. Vršnak, M. Temmer, & A.M. Veronig: C*oronal holes and solar wind high-speed streams: II. Forecasting the geomagnetic effects*
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M. Temmer, B. Vršnak, & A.M. Veronig: *Periodic appearance of coronal holes and the related variation of solarwind parameters* **Solar Phys. in press** (2007); available online at http://dx.doi.org/10.1007/s11207-007-0311-x

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B. Vršnak & T. Žic: *Transit times of interplanetary coronal mass ejections and the solar wind speed*
Astron. & Astrophys. submitted March 2007

Brief summary of main results

Contents:

1. Coronal holes and mapping of the solar wind high speed streams (HSSs)
2. Coronal holes and predicting the associated geomagnetic disturbances
3. Transit times of Interplanetary Coronal Mass Ejections (ICMEs):
   a) the effect of the solar wind speed
   b) the effect of the source region position
   c) the effect of the ICME density
   d) the kinematical ICME model
4. The CME acceleration phase
5. Formation of coronal MHD shock waves

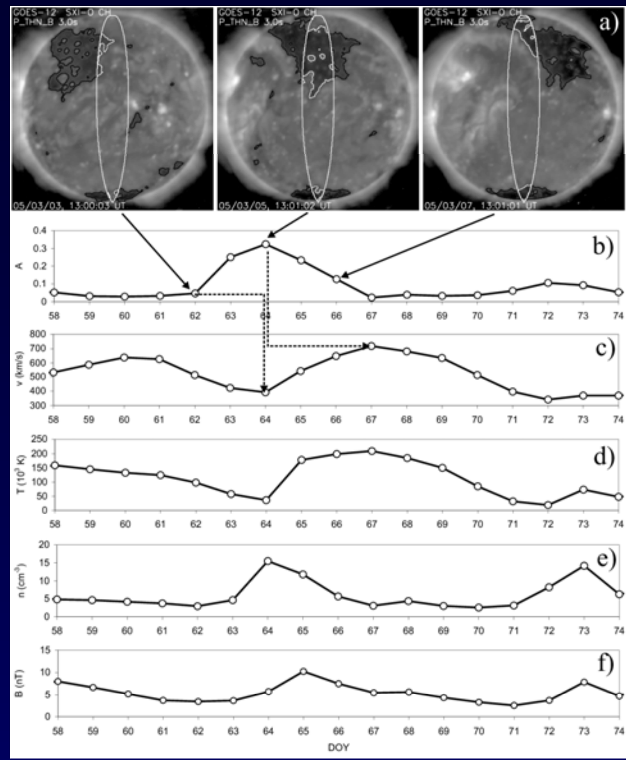
1. Coronal holes and mapping of the solar wind high speed streams

An empirical relationship between the area/position of coronal holes (CHs) and the characteristics of the associated high-speed streams (HSSs) in the solar wind is established. A procedure is developed, providing forecasting of the HSS velocity and density, which are important parameters for estimating the ICME transit time. In periods of low solar activity the solar wind speed *w* at a given moment *t* can be predicted using the expression:

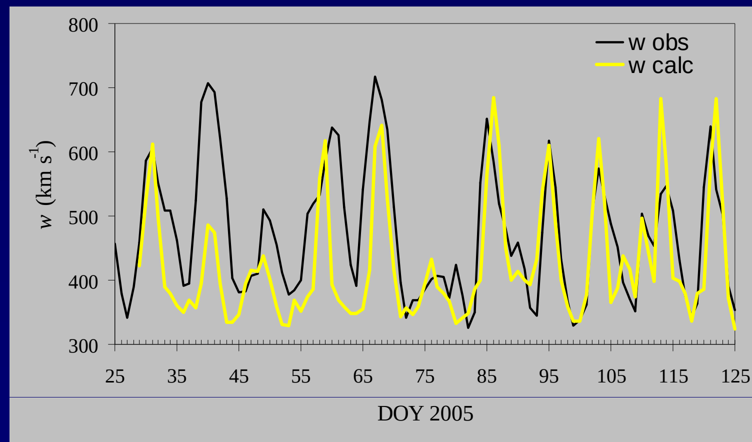
$$w(t) = 350 + 900 \times A(t^*),$$

where $A(t^*)$ is the CH fractional area in the 20 deg wide central-meridian bin, measured 4 days earlier. Analogous relationships are found for the density *n* temperature *T* and magnetic field strength *B*.

(Vršnak et al. 2007, Solar Phys. 240, 315)

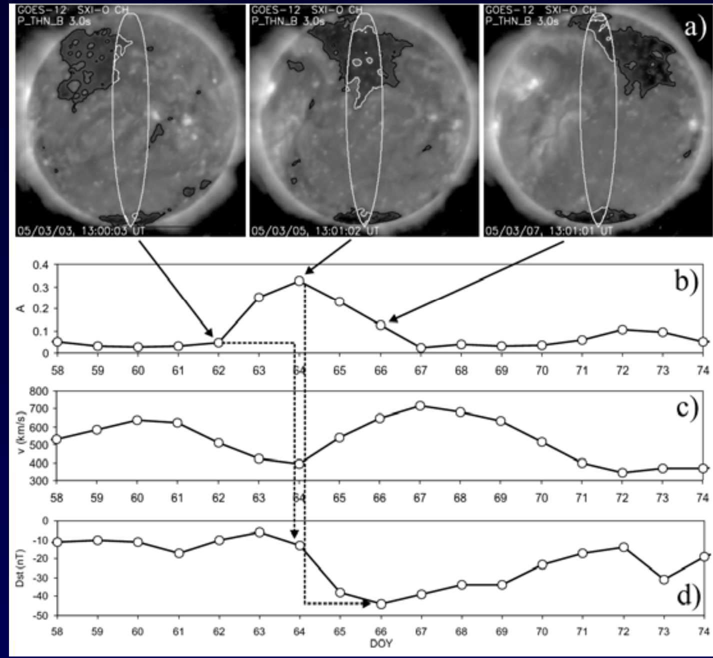


Measurements



Comparison of the observed and calculated solar wind speeds

2. Coronal holes and prediction of the associated geomagnetic disturbances



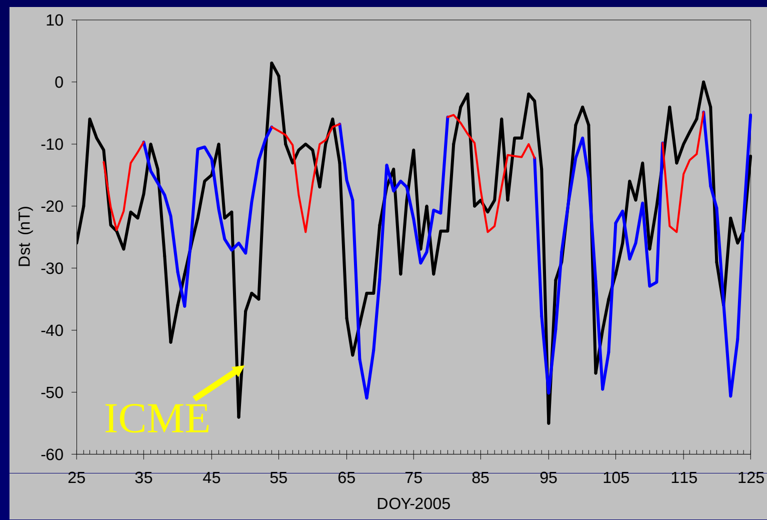
Measurements

An empirical relationship between the area/position of coronal holes (CHs) and the strength of geomagnetic disturbances caused by the CH-associated HSSs is established. A procedure is developed, providing forecasting of the related *Dst* changes. In periods of low solar activity the value of *Dst* at a given moment *t* can be predicted using the expression:

$$Dst = (65 \pm 25\cos\lambda)\,[A(t^*)]^{0.5},$$

where $A(t^*)$ is the CH fractional area in the 20 deg wide central-meridian bin, measured 4 days earlier, λ is the ecliptic longitude of the Earth, and ± stands for positive/negative CH polarity to account for the Russell-McPherron effect.

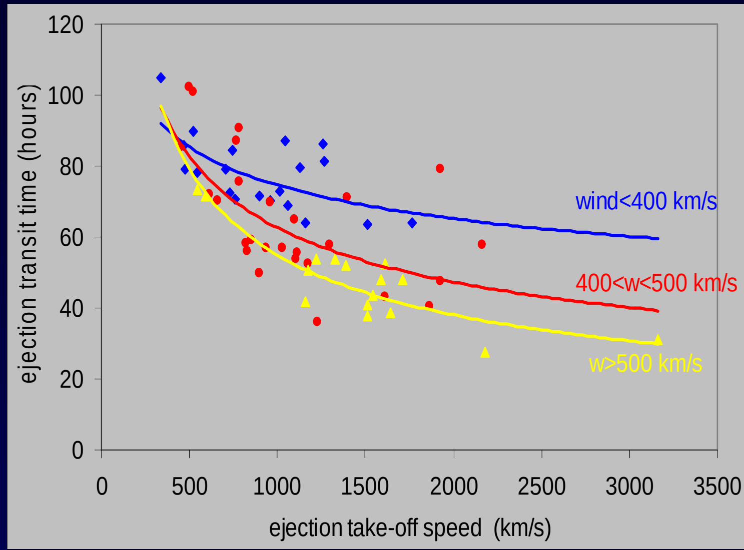
(Vršnak et al. 2007, Solar Phys. 240, 331)



Comparison of the observed and calculated *Dst* values

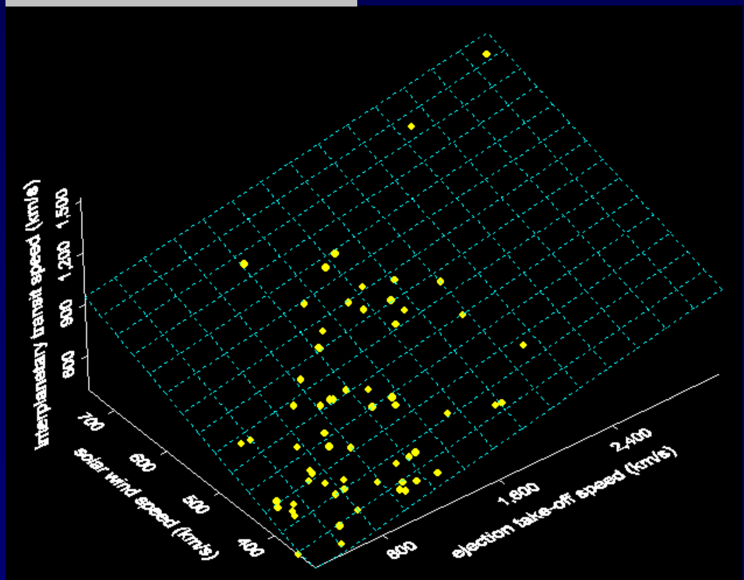
3. ICME transit times: a) the effect of the solar wind speed

(Vršnak et al. 2007, Astron. Astrophys. submitted)

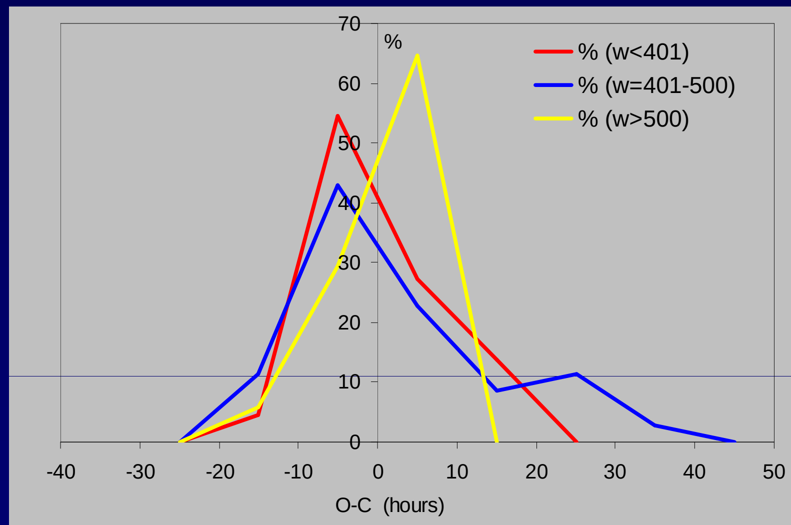


Dependence of the Sun-Earth transit times of interplanetary coronal mass ejections (ICMEs) shown as a function of the ejection take-off speed for three solar wind speed bins. ICMEs traveling through fast solar wind (yellow), on average arrive to the Earth 1 day before those traveling through slow solar wind (blue).

$$\textit{transit speed} = \frac{\textit{SunEarth dist.}}{\textit{transit time}}$$

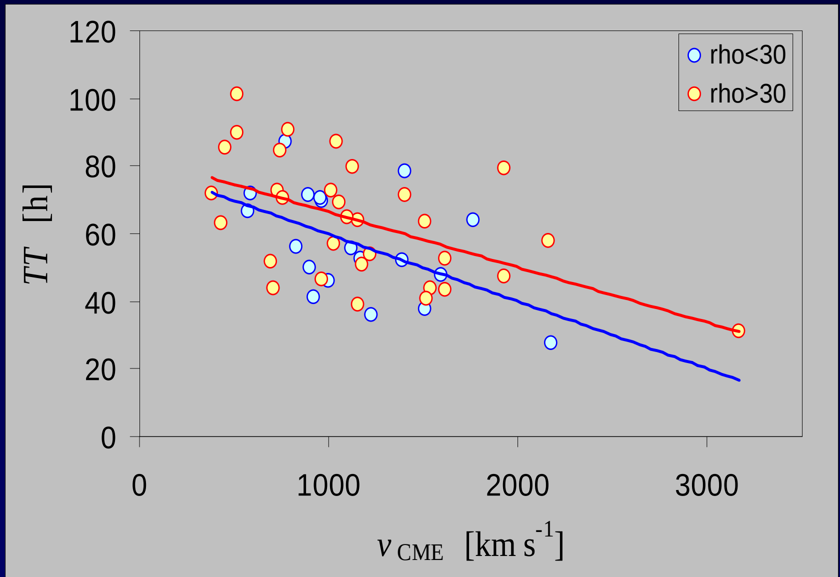


2-dimensional linear fit presenting the ICME transit speed as a function of the ejection take-off speed and the solar wind speed, from which the transit time can be estimated.



Distribution of the differences between the observed and calculated transit times; in more than 80% of cases the difference is within the ±10 hour interval.

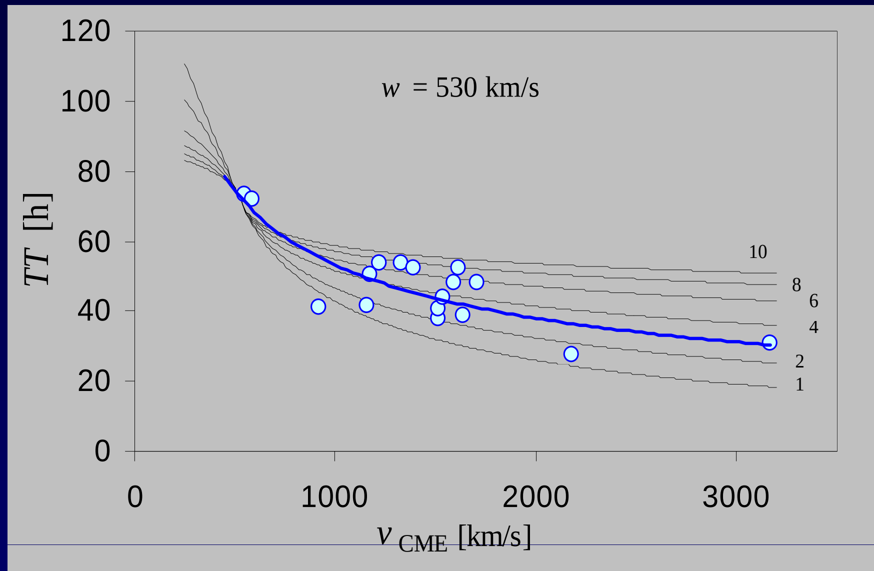
3. ICME transit times:
b) the effect of the source region position



Transit times of ICMEs launched from regions close to the solar disc center (blue dots and blue fit-line) on average are 5-10 hours shorter than transit times of ICMEs launched from regions close to the solar limb (red-yellow dots and red fit-line).

(Vršnak et al. 2007, in preparation)

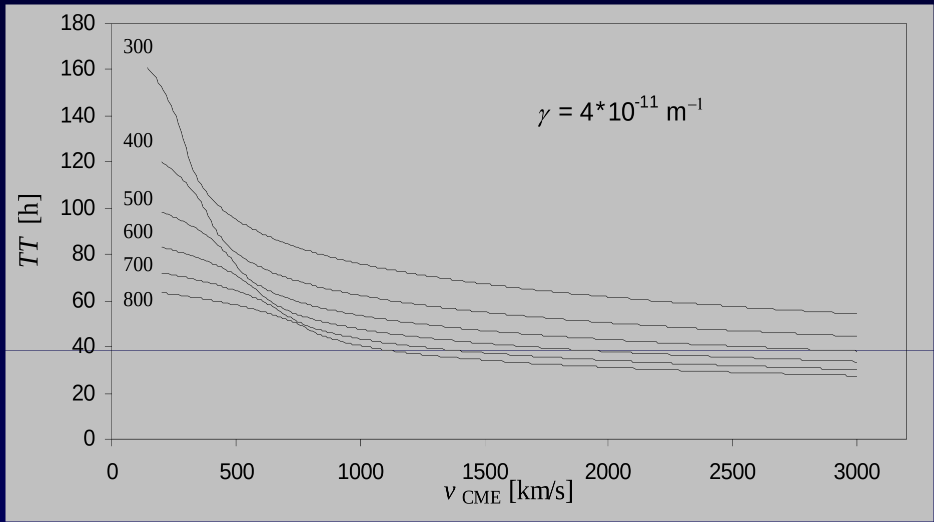
3. ICME transit times:
c) the effect of the ICME density

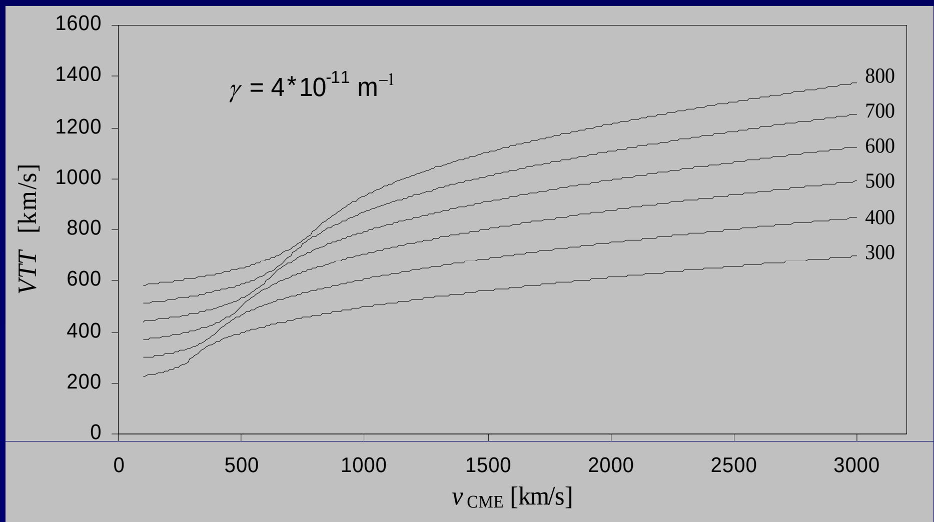


Transit times calculated from the drag-dominated equation of motion, considering different relative densities of ICMEs (1-10; black curves). The results are compared with the measured transit times of ICMEs propagating through the solar wind faster than 500 km/s (blue dots; blue line represents the power-law fit). The outcome indicates that the residual data scatter is most likely due to different ICME densities.

(Vršnak et al. 2007, Astron. Astrophys. submitted)

3. ICME transit times: d) kinematical ICME model





Transit times *TT* are calculated using the drag-dominated equation of motion:

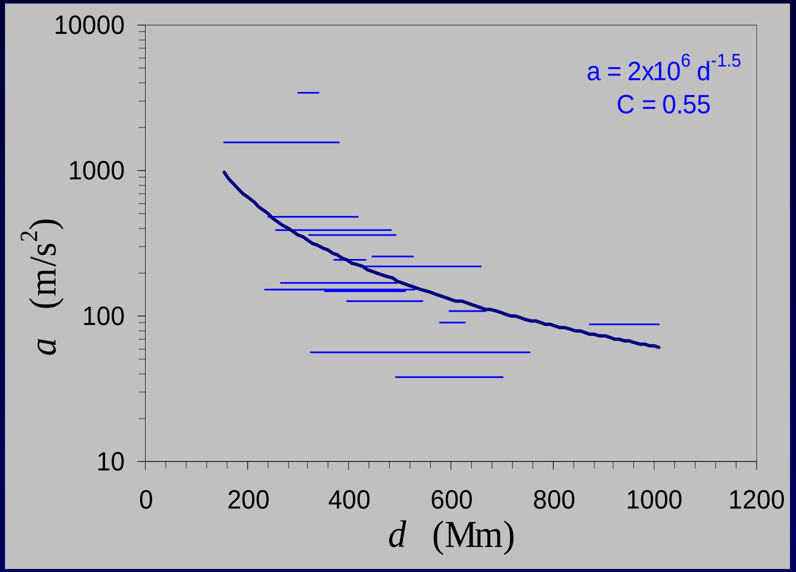
$$d^2r/dt^2 = -\gamma\,(v-w)|v-w|\ ,$$

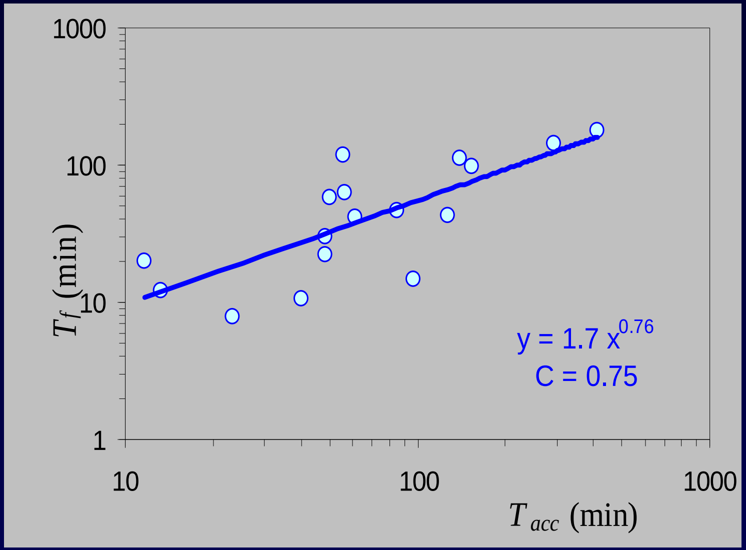
where v is the ICME velocity, and w is the solar wind speed. The parameter γ is taken to be constant (solar wind density decreases as r^{-2} and ICME mass is approximately constant). Different values of the take-off velocity (v_{CME} ; x-axis) and solar wind speed w are considered (written by the curves; km/s). The calculated span of values of *TT* and the transit speed *VTT*, is very close to the observed values.

(Vršnak et al. 2007, in preparation)

4. The CME acceleration phase

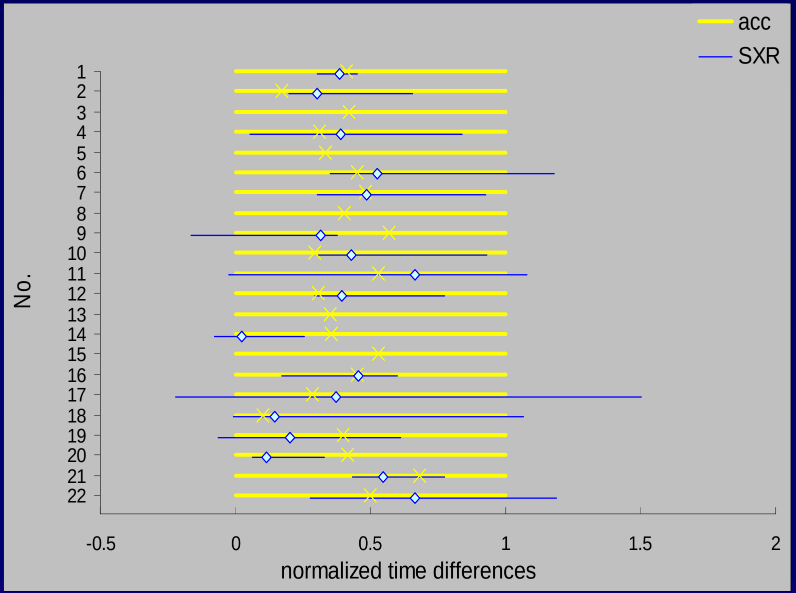
(Vršnak et al. 2007, Solar Phys. 241, 85)
(Maričić et al. 2007, Solar Phys. 241, 99)





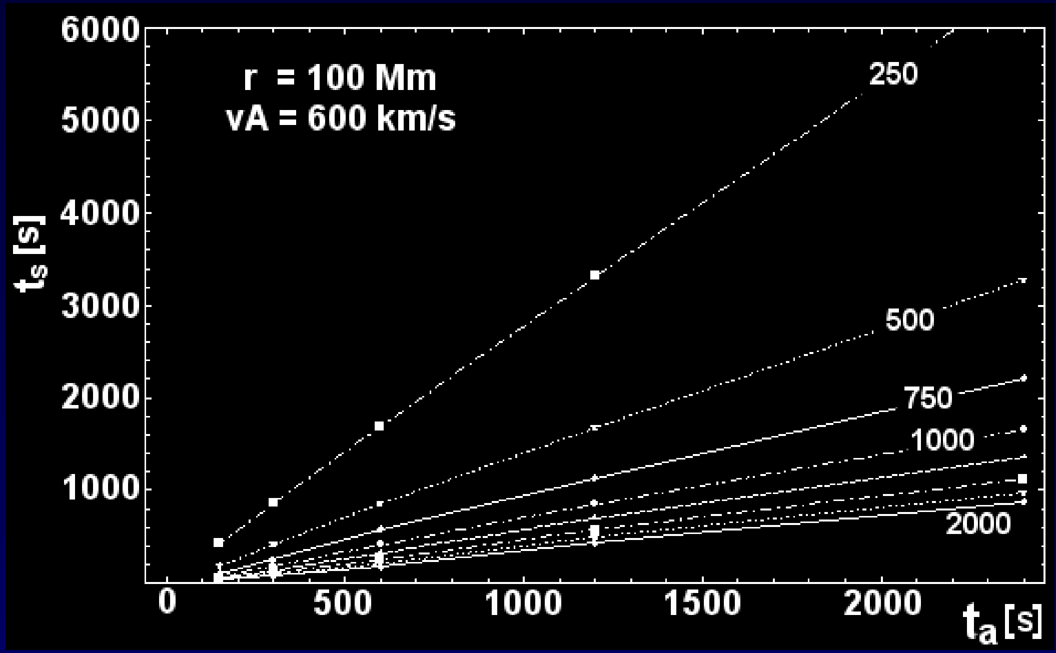
The duration of the acceleration phase T_{acc} and the duration of the impulsive phase of the associated flare T_f are closely related (close to be proportional).

Compact CMEs (small source dimensions *d*) are launched by higher acceleration than extended CMEs. The duration of the acceleration phase is shorter (not shown).



Comparison of the acceleration phase of 22 CMEs (yellow lines; crosses depict the acceleration peak) with the impulsive phase of the associated flare (blue lines; diamonds mark the fastest growth of the soft X-ray flux) reveals synchronization of the two phenomena and indicates that reconnection plays significant role in the CME acceleration.

5. Formation of coronal MHD shock waves



(Vršnak et al. 2007, in preparation)

The time needed for the shock formation t_s is primarily determined by the duration of the acceleration phase t_a of the source region expansion (3-dimensional piston). It also depends on the peak velocity v_m (indicated by the lines shown in the graph; km/s), peak acceleration ($a = v_m/t_a$), external Alfven velocity (v_A), Alfvenic Mach number of the source surface ($M_A = v_m/v_A$), and to a certain degree on the initial source dimension (r). The same holds for the distance at which the shock forms. The piston is not necessarily superalfvenic, i.e., the shock forms also for M_A<1; however, the time/distance becomes very large for small Mach numbers.